Possible Field-Tuned SIT in High-T$_c$ Superconductors: Implications for Pairing at High Magnetic Fields

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(Dated: February 2, 2008)

The behavior of some high temperature superconductors (HTSC) such as $La_{2-x}Sr_xCuO_4$ and $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$, at very high magnetic field, is similar to that of thin films of amorphous InOx near the magnetic field-tuned superconductor-insulator transition. Analyzing the InOx data at high fields in terms of persisting local pairing amplitude, we argue by analogy that local pairing amplitude also persists well into the dissipative state of the HTSCs, the regime commonly denoted as the "normal state" in very high magnetic field experiments.

PACS numbers: 74.72.-h, 74.78.-w, 74.40.+k

In this paper we show that the behavior of some high temperature superconductors (HTSC) such as $La_{2-x}Sr_xCuO_4$ [1] and $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ [2], at very high magnetic field is similar to that of thin films of amorphous indium oxide (InOx) near the magnetic field tuned superconductor-insulator transition (SIT). Comparing the details of the behavior of these two systems we conclude that the important ingredients in understanding the response of HTSC at low temperatures to a high magnetic field are their quasi-two-dimensional nature and low superfluid density [3], which make the HTSC system highly susceptible to phase fluctuations [4]. Upon the application of magnetic field, we conjecture that the single Cu-O layer undergoes a magnetic-field-tuned superconductor to insulator transition at a critical field of order of the mean-field upper critical field (denoted as $H_{c2}(0)$ [5]). Further increasing the magnetic field beyond $H_{c2}(0)$ weakens the tendency towards a Bose-dominated insulating phase, very much what is observed in our InOx films [6]. We thus conclude that the regime denoted as the "normal state" in the very-high field experiments of Ando *et al.* [1, 2] includes a large pairing susceptibility (i.e. local pair amplitude) that persists to fields as high as $\sim 3H_{c2}(0)$.

Understanding the nature of the normal state of HTSC is an important part of understanding the cause of superconductivity in these materials. In particular, understanding the underlying normal state in the temperature range where the materials are superconducting has been attempted in many experiments. For bulk low-temperature BCS superconductors (LTSC) this is easily accomplished by the application of a magnetic field larger than the upper critical field H_{c2} [5], thereby breaking all pairs and usually revealing an underlying Fermi liquid state. However, attempting such a procedure for HTSC has proven difficult due to the intense magnetic fields required and the fragility of the vortex state. While dissipation due to the melting or depinning of the vortices is easily achieved, recent experiments indicate that pairing and some form of local superconducting coherence persist to very high magnetic fields [7, 8, 9].

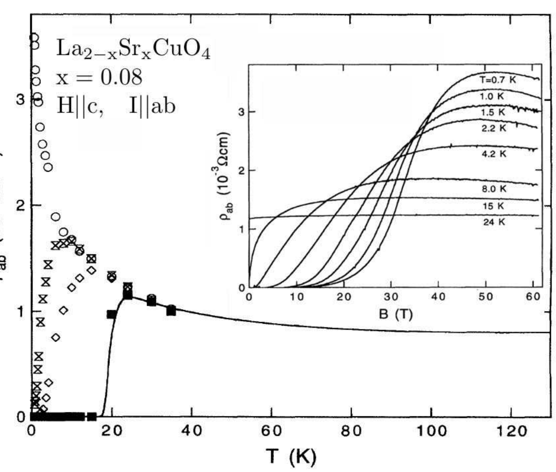

FIG. 1: A combination of Fig. 1(inset) and Fig. 2 (main panel) reprinted from Ando *et al.* [1]. ρ_{ab} is the in-plane resistivity of $La_{1.92}Sr_{0.08}CuO_4$ in perpendicular magnetic fields of 0 (solid line), 10, 20, and 60 T. The inset shows isotherms of magnetoresistance. Note the negative magnetoresistance above ∼50 T below ∼2 K.

An influential early attempt to reveal the underlying normal state of a prototype HTSC system was the seminal study of $La_{2-x}Sr_xCuO_4$ (LSCO) by Ando *et al.* [1]. Using pulsed fields up to 60 T, these authors concluded that the resistivity revealed at the high magnetic fields probes the behavior of the normal state [10]. A logarithmic divergence with a large coefficient was measured at low temperatures throughout the underdoped regime, which prompted many explanations for this unusual "normal state" [10]. However, not much attention was given to the peculiar result that a negative magnetoresistance starts to develop at the highest fields and lowest temperatures, an effect clearly seen in Fig. 1 (which is adapted from the data of Ref. [1]). An intriguing observation is that the magnetoresistance peak at low temperatures occurs at a field of order of the mean-

field-zero temperature value of H_{c2} that we would expect for this short coherence length ($\sim 20\mathring{A}$) superconductor. Taking this interpretation at face value, this means that at $0.7K$, for $H \leq 52$ T, the large resistance of the sample is dominated by weakly localized pairs, while above the peak for $H \geq 52$ T, pairs start to dissociate at a faster rate, giving rise to a negative magnetoresistance as the system slowly approaches a state that does not support pairing. This in turn suggests that the true superconducting transition is dominated by phase fluctuations. Unfortunately, much higher magnetic fields are needed to test whether the magnetoresistance continues to decrease to values of order of the resistance observed in zero magnetic field at higher temperatures. However, we note that the proposed interpretation is independent of the pairing mechanism or symmetry (e.g. d-wave vs. s-wave) of the order parameter and thus can be tested on other quasi-two-dimensional superconductors with low superfluid density [4].

Indeed, such a magnetoresistance peak was first observed by Paalanen *et al.* [11] in their investigation of the nature of the insulating state in InOx films near the SIT. More recent studies of SIT in thin superconducting films of amorphous MoGe [12] and InOx [13, 14] revealed a similar peak. In particular Steiner and Kapitulnik [13] were able to tune the insulating behavior of their InOx films in a fashion that allows a direct comparison with HTSC. Fig. 2 shows such results on an InOx sample that mimics the behavior of the LSCO shown in Fig. 1. We will return to the comparison between this InOx film and HTSC after we discuss the general properties of our InOx films and their SIT behavior.

Indium oxide is an amorphous low-carrier-density superconductor ($n \sim 10^{20} - 10^{21}$ carriers/cm^3) [15, 16] and was used previously in the study of the SIT [17]. Films of thickness 200 to 300 $\mathring{A}$ were prepared by electron beam evaporation of sintered In_2O_3 onto an acid-cleaned silicon nitride substrate [15]. $R_\square$, T_c, and the overall SIT of the films were varied by adding oxygen during growth and by the subsequent careful annealing of the samples [13]. The linear sheet resistance was measured using standard four-point lockin techniques at frequencies from 3 - 17 Hz and excitation currents 0.1 - 5 nA; the highest resistance sample was measured at dc.

To illustrate the controllability of the properties of the InOx films as pertain to their insulating behavior we show in this paper three films (of the dozen or so films prepared and measured) of different normal-state $R_\square$ and thickness for which the resistance was measured down to 50 mK and at magnetic fields up to 16 T. The sample which is of particular interest to us for a direct comparison with HTSC was also measured at fields up to 32.5 T. Except for the very low fields, for all samples, we observe a behavior similar to that shown in Fig. 2a, where the data is dominated by the presence of a resistance envelope. The curves at progressively higher magnetic fields follow

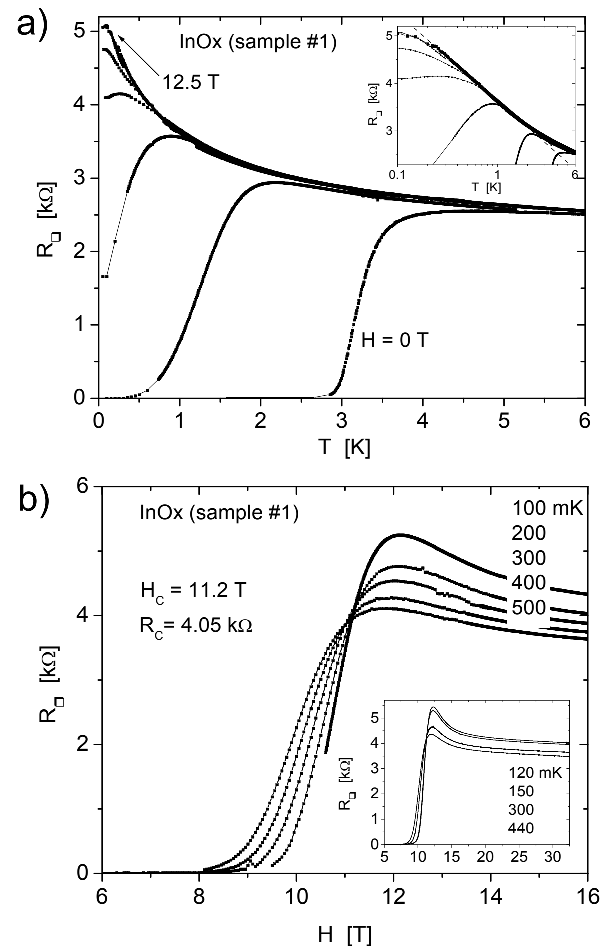

FIG. 2: (a) Resistive transitions of sample #1 showing the resistance envelope. The fields are 0, 8.0, 10.5, 11.2, 11.5, 12.0 and 12.5 T. The inset shows the logarithmic behavior of this sample's envelope before a low temperature saturation (see text). The dashed line is a guide to the eye. (b) Magnetoresistance isotherms at five temperatures. The inset shows the magnetoresistance up to 32.5 T, where the peak is the highest at the lowest temperature of 120 mK.

the envelope to lower temperatures before they deviate toward zero resistance. From the lower field portion we determine the mean-field upper critical field, a procedure described in detail elsewhere [13]. The WHH [18] determination of $H_{c2}(0)$ gives the values 13, 9.5 and 9 T for samples #1, 2 and 3 respectively with a a zero temperature coherence length $\xi(0) \approx 50\mathring{A}$ [19].

The resistive envelope presented here is qualitatively different from other reports on sputtered InOx [17] in which resistive curves appear to splay off from a common temperature, typically with wider transitions (see Fig. 1 in [17]). That pattern is more consistent with a granular system where the overall behavior is dominated by the Josephson phase-coupling between grains of fixed T_c. By contrast, in our films most of the transition seems to be dominated by amplitude fluctuations, with a final phase-dominated SIT at low temperature.

At high fields and low temperatures the InOx films

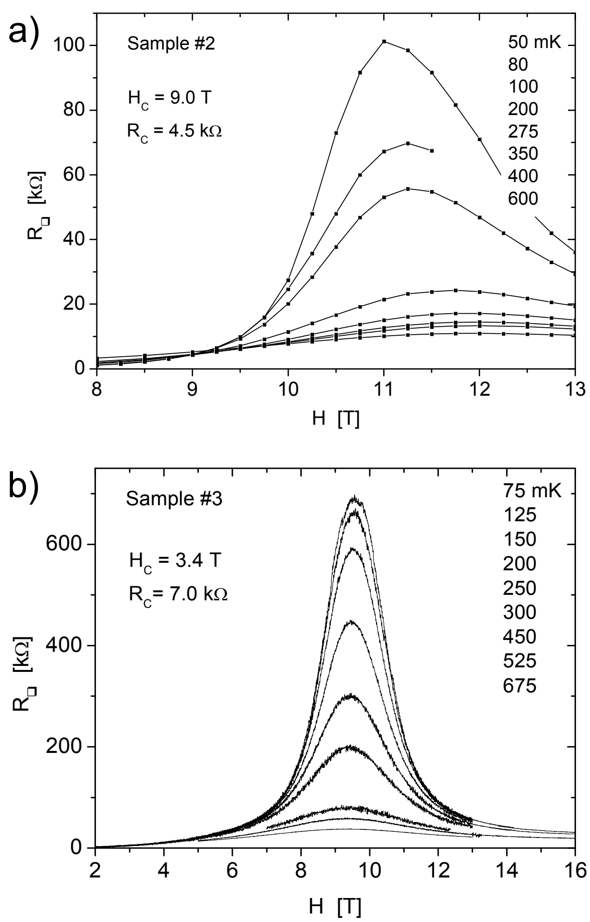

FIG. 3: Magnetoresistance isotherms for two samples with increased disorder relative to Fig 2. Crossing points at $\{H_c, R_c\}$ mark the SIT.

show signatures of a magnetic-field-tuned SIT [16, 20, 21, 22]. In Fig. 3 we show the resistance at high fields for the other two films. Following a sharp rise in resistance the isotherms *of all samples* go through a crossing point (H_c, R_c), a signature of a zero temperature quantum phase transition. Close inspection of the crossing indicates that the transition broadens at very low temperatures, $\Delta H_c/\langle H_c\rangle \sim 1\%$, a feature previously discussed by Mason and Kapitulnik [22]. Nevertheless, we can use $\langle H_c\rangle$ to scale the data using the usual one-parameter scaling form [23]: $R(H,T) = R_c\mathcal{F}\left(\frac{H-\langle H_c\rangle}{T^{1/z\nu}}\right)$, similar to [17]. The fit gives $z\nu \simeq 1.3$, in agreement with other measurements on MoGe [20, 22] and InOx [17]. Above the crossing point the resistance increases with decreasing temperature, marking an insulating phase at fields that are clearly lower than $H_{c2}(0)$. $\langle H_c\rangle$ decreases with disorder while R_c increases, and is thus non-universal [20, 22].

The tendency towards a Bose-insulating phase does not persist and upon further increase of the magnetic field the isotherms reach a maximum and then start to decrease. The resistance at the maximum increases roughly exponentially with temperature, with apparent saturation at the very lowest temperatures. The maximum for all samples is very close to the mean-field $H_{c2}(0)$. This is expected if we attribute the peak to a decrease in pairing susceptibility and a crossover of the system from being Bose-particle to Fermi-particle dominated. However, it does not appear, based on the available data range, that the resistance saturates at the highest accessible field. Focusing on sample #1 we measured it at fields up to 32.5 T (see inset of Fig. 2b). We note that the resistance at the lowest temperature (120 mK), at 32.5 T, is ~ 4 kΩ, which is a factor of ~ 1.7 higher than the zero field normal state resistance as extrapolated from the temperature dependent resistance above the transition. Theoretically, for a simple metal with the characteristics of this film, we expect a small [24, 25] $\Delta\rho/\rho_n \sim 10^{-3}$ [26] and diminished weak-localization effects in such high fields [27]. *Thus it appears that even at 32 T the film has not returned to its expected normal state.*

The insulating state above the crossing point is even more dramatic in the films with higher $R_\Box$, as shown in Figure 3. On the high field side of the peak, the isotherms all tend to decay to resistances ≤ 20 k$\Omega/\Box$, but still much above the normal state resistance. The increase in resistance in these stronger insulators is several orders of magnitude before the resistance starts to saturate at very low temperatures. Taking fixed-field cuts through the isotherms [14], we find that the resistance increases as $R_\Box \sim e^{T_A/T}$ with a characteristic activation energy $k_B T_A$. T_A is of the order T_{c0} (about 1 K) for the strongest insulator (sample #3), while for the weak insulator (sample #1) it is substantially lower; based on the limited temperature range of the data, we estimate T_A to be at most ~ 100 mK [13].

Let us now turn our attention to a comparison with the quasi-two-dimensional HTSC system. An envelope pattern similar to that seen in Fig. 2a was also observed by Ando *et al.* [1] for the in-plane resistivity of underdoped $\mathrm{La_{2-x}Sr_xCuO_4}$ (LSCO) in a pulsed magnetic field. Their data, (Fig. 1), shows an overall resistance envelope with curves at different fields splaying off at progressively lower temperatures. The inset to Fig. 1 shows isotherms of the resistance which, at the lower temperatures, increase dramatically with field before peaking and slowly starting to decrease, similar to the behavior of the InOx shown in Fig. 2b. Both the temperature and magnetic field scales of their experiment are much higher than for the InOx films – the envelope persists up to 50 T and the zero-field transition temperature was almost 20 K, but the qualitative resemblance to our data is clear. In fact, even quantitatively these two systems are similar, showing a logarithmic temperature dependence of the resistivity envelope $\Delta R/R = AR_\Box log(1/T)$ with a prefactor $A \gg pe^2/2\hbar\pi^2$ (for any reasonable p), indicating that the observed $log(1/T)$ behavior is not due to conventional weak localization. Specifically for sample #1 (see the in-

set of Fig. 2a), $A \approx 1.3 \times 10^{-4}\ \Omega^{-1}$ as compared to an expected weak localization slope of $A \approx 2.4 \times 10^{-5}$ (for $p = 2$ [27]). The fact that the InOx films' resistance saturates at low temperatures while that of the HTSC does not may be the effect of the weak interlayer coupling. Indeed, a ground plane in proximity to a SIT in MoGe films was shown to overcome the saturation [28]. Additionally, the InOx films show a sharply defined crossing point in Fig. 2b, while the $La_{2-x}Sr_xCuO_4$ samples in Fig. 1 do not exhibit a crossing point. This might be attributed to the relatively high temperatures at which the HTSC data were taken, and the weak three dimensional coupling that disrupts the scaling [22, 29].

The series of similarities between the HTSC and InOx data may point to a new understanding of the normal-state phase found in the cuprates for high fields. What was previously denoted the "normal state" is more likely the development of a Bose-insulating phase in which incipient superconductivity persists. The magnetic field appears to drive two competing effects: increasing the field promotes phase-fluctuations which drive the system further Bose-insulating, while also directly depairing the Cooper pairs, thereby weakening this boson-dominated phase. The former effect was first proposed by Doniach and Inui [30] in the context of HTSC. The latter suppresses the superconducting amplitude until superconductivity is destroyed entirely. The two mechanisms together give rise to the isotherm peak which reflects an underlying existence of H_{c2} above which pairs are broken. The fact that the complete magnetoresistance peak was not observed previously in the cuprates is a consequence of their very high magnetic field scale. As we noted above, a close examination of the data of [1] shows that above 50 T the magnetoresistance starts to decrease. Accepting that the envelope behavior and the peak in the magnetoresistance in the two systems have similar sources, we expect that for $La_{2-x}Sr_xCuO_4$, increasing the magnetic field to ~ 200 T will yield results similar to that seen in the inset to Fig. 2b for InOx up to ~ 30 T in which the pair-amplitude is *very* slowly suppressed out to high fields and the system retains a vestige of superconductivity at magnetic fields well above H_{c2}. Our analysis is completely consistent with recent Nernst effect measurements [7, 8, 9] in which a strong Nernst signal was measured at fields well above the mean field H_{c2} [5] for several cuprates including $La_{2-x}Sr_xCuO_4$ and was interpreted as persisting vortices [7]. Finally, we note that studies of more disordered (possibly more underdoped) highly anisotropic HTSC samples may yield stronger insulating behavior similar to that found in more disordered InOx films.

Acknowledgments: We thank Yoichi Ando and Steven Kivelson for helpful discussions, and Tim Murphy and Eric Palm for their help at the NHMFL, funded by the NSF and the State of Florida. MAS and AK supported by NSF Grant: NSF-DMR-0119027.

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